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VOLATILE COMPONENTS AND CONTINENTAL MATERIAL OF PLANETS

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16. Abstract It is shown that the continental material of the terrestrial planets varies in composition from planet to planet according to the abundances and composition of true volatiles (H ₂ O, CO ₂ , etc.) in the outer shells of the planets. The formation of these shells occurs very early in a planet's evolution when the role of endogenous processes is indistinct and continental materials are subject to melting and vaporizing in the absence of an atmosphere. As a result, the chemical properties of continental materials are related not only to fractionation processes but also to meltability and volatility. For planets retaining a certain quantity of true volatile components, the chemical transformation of continental material is characterized by a close interaction between impact melting vaporization and endogenous geological processes.			
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VOLATILE COMPONENTS AND CONTINENTAL MATERIAL OF PLANETS

K. P. Florenskiy¹ and O. V. Nikolayeva

Generalization of data on the continental material of crusts of terrestrial planets indicated that it is individual for each planet and changes naturally from planet to planet in correlation with the quantity and composition of the truly volatile components (H_2O , CO_2 , etc.) in the system of outer planetary shells. These shells, including the continental material, are formed very early, in the period which completes the growth of the planets and opens their geological history, when the role of endogenous processes is problematic, and during the intensive bombardment of the surface, the material not only melts, but also partially or completely evaporates in a system which is open predominantly for space. The chemical features of the continental material could be linked to fractionation not only for low melting point, but also volatility. On the planets which retain a certain quantity of truly volatile components, the chemical conversions of the material in this period occur in close interaction of the impact processes of melting and evaporation and normal geological processes inherent to this planet, for example, water or aeolian sedimentation processes. The individual nature of the continental material could be due to the uniqueness of these interactions on each planet.

Introduction

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With the development of space research, the level of knowledge about the composition and structure of bodies in the solar system has basically changed. However, the fundamental generalization of new data has only just begun and some old concepts have not been sufficiently touched upon; these are ideas which are perceived as hard-and-fast and coexist with new facts that contradict them [1 - 3].

¹The plan for this article belongs to K. P. Florenskiy; he was constantly working on it during the last years of his life, weighing the overall statement of the problem and individual, specific questions, and repeatedly discussing them in unhurried joint discussions, especially in working on "Essays on Comparative Planetology" [1]. Many key conclusions of the article were included in the Essays; the introduction was especially written for the article of K. P. Florenskiy and the contents of the abbreviated summary were approved. Now when Kirill Pavlovich is no longer with us, I considered it my duty to complete this work, trying to preserve the calm tone of presenting the developed ideas which was inherent to Kirill Pavlovich. Colleagues of the laboratory of comparative planetology

At the same time the expansion in the study objects requires a review and pinpointing of a number of the established concepts. One of these concepts is volatile components. The migrational ability of material in the gas phase differs strongly from the mobility of the condensed phases. In this sense, the "geochemistry of gases" is sometimes mentioned [4] as an independent section of geochemistry, never mentioning the "geochemistry of liquids," for example, where magma and the surface waters should be discussed jointly. However, all materials strive for equilibrium with the gas phase, i.e., possess a varying degree of relative volatility. We should thus classify with the volatile substances those whose volatility is include in studying this specific process by the methods which have a definite threshold of sensitivity, and whose behavior makes it possible to contrast them to the behavior of condensed phases.

This analysis is necessary in space chemistry where in a broad range of pressures we encounter a temperature interval from tens of thousands of degrees, where all the materials are in a volatile state in the form of gas or plasma, to temperatures which approach zero degrees Kelvin when the properties of volatility disappear.

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There are weighty grounds for believing that the solid bodies in the solar system grew during collisions. Traces of this method of growth are imprinted, for example, in the brecciation of meteorites and bedrock of the Moon, in the abundant craters on the surface of space bodies. Among the numerous studied solid bodies, planets of the terrestrial group, Moon, satellites of Mars, Jupiter and Saturn, only some, including the Earth, did not maintain the morphological traces of these universal events which were erased by the active cyclic renewal of the surface. The substance of any solid space body during its growth was affected to a certain measure by the impact processes. This is an empirical fact and is undoubted. However, the chemical transformations of material during these processes have only been studied recently and are only clear in the most general features.

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* Numbers in right margin indicate pagination in original text.

These processes are unusual for the terrestrial geologist and geochemist. They have colossal energy (often exceeding the energy of the largest volcanic eruptions) which is released instantly and locally in the form of an explosion, discharging material from great depths. Upon impact, the pressure can reach thousands of kilobars, while the temperature can reach thousands of degrees and usually the silicate rock is not only crushed and melted, as under the influence of endogenous factors, but is also converted into gas, is evaporated [1, 5, 6]. Of course such normal volatile components as water, carbon- and nitrogen containing compounds and inert gases are vaporized; they could be called truly volatile components [1]. However, even at 1500 - 2500°C, K and Na are easily evaporated from the silicate material, Si and Fe become moderately volatile, and it is more difficult for Al, Ti, Ca, and Mg to pass into gas [6 - 8]. Thus, in the impact-explosive processes, essentially all the components of the material could pass through the gas phase and become volatile. This is the basic geochemical difference between the impact processes and the normal geological processes.

The impact-explosive transformations of material are thermodynamically extremely nonequilibrium [1]. The gas which emerges upon impact, which corresponds in properties to low-temperature plasma, is next to colder streams of melt and particles of solid rocks, the material discharged from the depths is moved at high speeds, reaching kilometers per second, and in the overwhelming majority of cases the conversions occur under conditions which are open to the vacuum of outer space for the planetary atmosphere. All of this guarantees great possibilities for redistribution and differentiation of the material in the gas phase.

Experimental modelling of chemical transformations of rock in impact events is extremely complicated. The normal experiments on melting, evaporation and condensation of material in a vacuum at temperatures to 3000°C (for example, [7 - 9]) create the necessary chemical basis for studies; however, the application of these data to natural phenomena requires great caution. For example, it is common knowledge that if an impact load is applied before heating, then there is a severe change in the mobility of the alkalis [10],

while with shock heating, the nature of evaporation and condensation of matter is greatly determined by kinetic factors [11,12]. In addition, the compositions of gas, residual phase and condensate are closely related to the quantity and composition in the simulated system of truly volatile components [8, 13]. Thus, when they are missing, there is an absolute dominance in the gas of simple atomic forms of elements (K, Na, Ca, Mg, Fe, Al) or suboxides (SiO, TiO) [14], but in the presence of water, sodium, for example, is evaporated in the form of an NaOH molecule [15]. Unfortunately, because of the difficulty of studying the systems with truly volatile components, there is only fragmentary work of this type.

It was noted in geochemical study of impact craters on Earth that the nature of the products of impact-explosive transformations differs significantly depending on whether they took place in the presence of considerable quantities of H₂O and CO₂ (mobilized from sedimentary rocks and the hydrosphere) or increased quantities of CO₂ alone (with the participation of predominantly carbonate rocks) or with small quantities of both components (in crystalline rocks) [13, 16]. These types of relationships are well known for magmatic crystallization. For impact processes, they have been poorly studied; however, the very fact that they exist allows us to raise the question of the possibility of a similar relationship on a planetary scale, for planetary bodies with different compositions of atmospheric gases and different reserves of water in their external shells.

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As shown 20 years ago [5], the planetary atmosphere (and hydrosphere) is inevitably formed simultaneously with the growth of its solid body during impact-explosive events. Many researchers later came to the same conclusion independently [17 - 19]. It was recently recognized more distinctly that the processes of impact melting, evaporation, crystallization and condensation of matter affect the existing gas and liquid and solid material on the planet [1]. The material of the planetary

mantle, its crust and gas shells of course passed to a certain measure through them. However, as stressed by V. I. Vernadskiy, the genetically unified set of the most external shells of the planet taken as a whole, differs in precisely this way from the deep zones in which: here and only here, all three physical states of matter, solid, liquid and gaseous could be different [20]. The set of external shells of the planet, atmosphere, hydrosphere and crust, should be viewed jointly as a single heterophase planetary mantle (although on different planets, the atmosphere (and the hydrosphere) could be reproduced to a varying degree all the way to complete disappearance). The heterophase mantle of the planet plays the role of a buffer shell between the depths of the planet and the vacuum of outer space [1]. In this article we would like to attract the attention of researchers to the possible link between the components of varying volatility in the material of the heterophase mantles of terrestrial planetary bodies.

Facts and Hypotheses

The factual material, except for the very latest, was summarized in "Essays on Comparative Planetology" [1], and some of the generalizations made there concern the essence of the question under discussion. As shown in this work, most of the truly volatile components are separated in intensive impacts in the transitional period, the period of the end of growth of the planet and the beginning of its planetary development; they are either lost by the planet or are immediately involved in the normal geological processes with the participation of solid matter. Only after a certain time interval in the planetary stage of life does endogenous melting of the mantle material begin; it results in the formation of crust material of basalt type, of which the overwhelming mass is geologically superposed on the more ancient crust material, the continental [1].

The effusive material of planets is mainly chemically uniform. On Earth, for example, the basalts comprise over 97% of all the volcanic material [21], while on the Moon, acid-composition glasses

are generally a mineralogical rarity. The basalts of different planets of course have certain chemical differences and it is important to study them to characterize the material in the area of formation of basalt magma. However, on the whole, endogenous effusive magmatism results in the same degree of planetary differentiation of material, basalt.

There is basically a different situation with the continental material of planets. The continental material of the Moon is anorthosite-norite-troctolite rocks, while the Earth is "granitoid" rocks. Whereas the continental material on Earth has been repeatedly transformed during cyclic processes, on the Moon where there is no atmosphere and endogenous activity ended early (about 2.5 billion years ago, i.e., on a terrestrial scale, already at the end of the Archean, early Proterozoic), the continental material was preserved from ancient times as it was essentially created. At the same time, the Moon provides us with a unique and important reference point. /1254

The Moon. From astronomical viewpoints, the Moon, rotating around the Earth, does not belong to the planets (which rotate around the Sun), but to planetary satellites; however, from a geochemical viewpoint, this is a truly planetary body since it has a spherical shape and is differentiated into shells [1]. The planetary mantle of this small body is reduced to the maximum and only consists of a crust. About 99% of the crust mass is continental matter, while the remaining 1% includes basalt matter of extensive, but shallow sea plains superposed on the bedrock. The dominant geological structures of the surface and the corresponding shapes of the relief of the bedrock are impact craters.

Because of the possibility of isotope datings of samples sent to Earth, and knowledge of the lunar geological structure, it was established that its continental material was formed in the time interval of about 4.5 to about 3.9 billion years ago, i.e., only in that period when intensive meteorite bombardment of the surface was continuing, completing growth of the body. Currently the lunar bedrock is the only planetary sample of that ancient time which

we can study by normal geochemical and petrographic methods.

Study of these rocks showed that they are mainly represented by breccias, polymictic, often multigeneration granulites and cataclasites with shell and blast structure. Thus from a petrographic viewpoint, the anorthosite-norite-troctolite rocks of the Moon differ sharply from the chemically magmatic rocks of the Earth which are similar to them and in complete correspondence with their age and geological position are mainly impact formations [1]. The continental rocks of the Moon with their strictly magmatic structures are encountered extremely rarely in the form of small single fragments in impact breccias or in regolith (product of low-intensive impact reprocessing of the surface lasting from 3.9 billion years ago to the present). Some of these particles with low content of the siderophile elements which are characteristic for meteorites have been viewed by certain authors [22] as residues of endogenous primordial-juvenile lunar bedrocks. It is believed that the hypothetical igneous plutonic rocks that were formed 4.5 - 4.2 billion years ago formed the ancient lunar crust that was then destroyed during impact events. A critical geological and geochemical discussion of this hypothesis [23, 24] takes into consideration the high likelihood of the formation and burial of the impact melts and the possibility of redistribution of the siderophiles during the impact processes. It should be stressed that according to the data of studying the crater discharges, the rocks of the lunar continental crust are represented by breccias from the surface and to depths of several kilometers, and according to the results of seismic indication, to depths of 20 - 25 km, and the nature of the material does not change strongly to depths of about 60 km (summary in [1]).

The chemical features of the continental material of the Moon have mainly been established fairly reliably; assessments of the total chemical composition of the continental matter fluctuate slightly [25 - 27]. In its chemical (but not petrographic!) characteristics (table 1), this substance could be described as feldspar, largely calcium ($An > 50\%$), primary plutonic rock of a normal series (of the tin gabbro type) (from [28]). With a

fairly high content of Al_2O_3 , CaO , MgO it is distinguished by an extremely low content of K_2O and Na_2O (only $<0.5\%$ total). In addition, the continental material of the Moon is essentially lacking water, carbon, nitrogen and the primary (captured) inert gases ([1, table 32], i.e., all the truly volatile components. It is essentially the absence of water, the main moving force of the cyclic processes, which explains the unique preservation of geological and petrographic structures of this material. /1255

TABLE 1
SOME DATA TO CHARACTERIZE THE CONTINENTAL MATERIAL
OF PLANETS

(1) Компонент, мас. %	(2) Малые планетные тела		(3) Крупные планетные тела	
	(4) Луна (по [26,27])	(5) Марс	(6) Земля*	(7) Венера**
SiO_2	44,94	(9) Основание по составу***	63,68	57,63 (52,03—64,93)
TiO_2	0,34		0,52	0,85 (0,17—2,09)
Al_2O_3	23,94		15,51	13,46 (15,65—22,34)
ΣFe в виде FeO	5,38		5,40	5,58 (2,44—9,87)
MgO	11,44		2,72	0,55 (0,31—1,20)
CaO	13,53		3,44	2,18 (0,37—3,51)
Na_2O	0,24		2,73	7,22 (5,75—8,44)
K_2O	0,06		3,01	4,99 (4,39—5,74)
U, г/т(10)	0,3	$0,2 \pm 0,14$	2,80	$2,2 \pm 0,7$
Th, г/т(10)	1,0	$0,7 \pm 0,35$	12,25	$6,5 \pm 0,2$

Key:

1. Component, % by mass
2. Small planetary bodies
3. Large planetary bodies
4. Moon (from [26, 27])
5. Mars
6. Earth
7. Venus
8. In the form of
9. Base by composition
10. g/T

* Recalculated from data of [21] (see text).

** Evaluated composition at site of landing of Venera-8, average and spread of values for 15 terrestrial rocks with content of K, U, Th similar (in limits of the analysis error) to that measured on Venus (see text).

*** See text; U, Th from [36]

The age of the continental rocks of the Moon is close to the age of the Moon itself as a planetary body, showing that the formation of the continental material occurred extremely early, back during the completion of the body growth. Many people, especially among the foreign researchers, in order to explain the early chemical differentiation of material with isolation of the continental crust prefer the model of complete melting of the external part of the Moon because of its hypothetically rapid gravitational growth up to about 4.5 billion years ago (in a later time for which we already have results of geological observations, this event was impossible). However, it is basically not possible to use the hypothesis of the "ocean of magma" which is widely employed by a number of researchers. There are grounds to assume that the effect of chemical differentiation of material can be obtained by local, but multiple impact-explosive factors [1, 5]. Separation here could even be more effective in the same way as this occurs in the rectification columns.

For example, under the influence of low-intensive but lengthy meteorite bombardment, the chemical effects of the impact processes are accumulated in the lunar regolith (summary in [1]). As compared to the initial rocks for it, the regolith as a whole and especially its small fraction reprocessed by impact are united by easily volatile alkali metals and moderately volatile silicon and iron. The intensity of the effects of selective evaporation can be very great; for individual particles, losses of Si are recorded up to 30% of its initial content, and over 90% for Na. The kinetic effects of separation of isotopes in this dynamic process result in a severe increase in weight of the isotope composition of Si, O, S and K. The loss of about 5% of very easily volatile Rb results in a paradoxical situation where the model Rb of Sr-age of regolith is more ancient than the age of the particles forming it [29, 30]. At the same time, the processes of impact melting, judging from the composition of regolith glasses, act mainly as a homogenizing factor. Thus, as is apparent in the example of Lunar regolith, on this small planetary body, which is open in relation to the vacuum of outer space, the chemical differentiation of material in the impact

processes is related predominantly to a certain loss of volatile components.

In light of the summarized empirical data on the Moon, the /1256
chemical composition of its continental material in which there are actually no truly volatile components at all, few low-volatile alkalis and dominance of aluminum, calcium and magnesium, can be viewed as a product of early chemical differentiation of material not only for low melting point, but also for volatility [1, 31, 32]. From our viewpoint, this problem deserves serious consideration. It would apparently be interesting to discuss data on the scattered elements and isotope composition of the continental rocks.

Mercury. This planet is the closest to the Sun and has not been extensively studied; it is almost three times larger in volume than the Moon. However, as shown by analysis of photomaterials, the geological structure of the surface and the history of development of these bodies are extremely similar. The planetary mantle of Mercury, like the Moon, is reduced to the maximum and consists only of a crust. The crust structure displays the same distinct separation into ancient continental (abundant craters) and superposition of sea (fewer craters) localities. The history of development of Mercury also reveals a stage of intensive meteorite bombardment of the surface, very early differentiation with isolation of a continental crust and somewhat later, rapidly diminishing area volcanism. The chemical composition of the Mercury surface rocks is also evidently similar to the composition of the lunar rocks, which is indicated by their similar geomorphological characteristics and the same reflective properties of the surface in the optical, infra-red and radioranges. At the same time, Mercury in its gross chemical composition differs noticeably from the Moon in the much greater content of iron (its mean density is roughly 1.5-fold higher than the lunar). But this difference is not influential either in the structure and composition of the surface, or in the geological history of these planetary bodies [1].

Mars. The geological structure of the surface and the main developmental stages of Mars are known [1, fig. 53], but one can only judge the chemical composition of its crust material from the results of analyzing the surface ground (as if on Earth we studied chemically only the Quaternary deposits and from them, by knowing the geological processes, should have guessed the existence of acid and base rocks in the Earth's crust).

Despite its small dimensions (weight only 0.1 of the Earth), Mars has a developed heterophase mantle which consists of the solid material of the crust, cryolitosphere (crust reservoir of predominantly aqueous ice), a small-mass solid-phase analog of the terrestrial hydrosphere, and atmosphere, carbon dioxide in composition and two orders less massive than the atmosphere of the Earth [1, table 34].

The presence (assume of a small quantity) of truly volatile components in the planetary mantle results in a considerable diversity in the surface processes; essentially on the entire surface there is wind reprocessing of material, its transfer and aeolian sedimentation; the presence of ice rocks has an influence everywhere in different forms of the relief, water-erosion valleys are encountered locally which were formed almost definitely by melting of ice during impact or volcanic events. The effusive activity on Mars in contrast to the Moon and Mercury was manifest not only in the form of vast area discharges, but also in the formation of several large shield volcanoes.

However, because it is impossible for liquid water to constantly exist on this cold planet which is far from the Sun, and there is no biosphere, the integral rates of surface transformations are not sufficiently great to erase the distinct signs of the ancient stage of intensive meteorite bombardment of the surface. The continental hemisphere of Mars has almost as many craters as the continents of the Moon and Mercury, although on the whole, the Martian impact craters are more eroded; they permit dating of the formation of structures of the Martian bedrock as approximately from 4.5 to 4 billion years ago [1]. Volcanic plains which are distinctly

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TABLE 2.

MEAN CHEMICAL COMPOSITION (% by mass) OF LOOSE SOIL (WITHOUT SURFACE CRUST) AT SITES OF LANDING OF VIKING-1 AND -2 ON MARS [33]

(1) Место посадки	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	K ₂ O	TiO ₂	SO ₂	Cl	(2) Гро- чек*	(3) Сумма
(4) Викинг-1»	44	7,3	17,5	6	5,7	0,5	0,62	6,7	0,8	2	91
(5) Викинг-2»	43	(7)**	17,3	(6)**	5,7	0,5	0,54	7,9	0,4	2	90

Key:

- | | |
|-----------------|-------------|
| 1. Landing site | 4. Viking-1 |
| 2. Others | 5. Viking-2 |
| 3. Total | |

* Including P, Mn, Na, but the content of each of them is below the detection limit.

**As at the landing site of Viking-1.

superposed on the continental structures are younger than 4 billion years, and judging from the morphology of the lava streams, are predominantly filled with basalt type matter [1]. However, the dominant relief-forming rocks of the continental elevations of Mars cannot at all be correlated with the basalt discharges and are geomorphologically similar to the rocks of the lunar continents.

Chemical analyses of 21 samples of loose fine-grained soil are available for two sections of volcanic valleys which are 6000 km from each other [33] (table 2). They display remarkable chemical homogeneity of material, differing only in content of S and Cl (accumulated in the form of salts in crusts on the soil) and evidently predominantly represented by clay minerals which are characteristic for products of change in rocks of base composition. However, it is known that the tested soil is not a product of weathering of local basalts (it is generally difficult under Martian conditions), but of allochthonous aeolian detritus [33]. With regularly repeating dust storms on Mars similar to that which prevented operation of the spacecraft Mars-2, -3 and Mariner-9, which covered the planet in a dust curtain for 2 months, redistribution and mixing of the aeolian material in a planetary scale are not doubted.

At the same time, researchers studying the composition of the aeolian ground, because of the high ratio of $\text{Ca}/\text{K}_2\text{O}$ in it excludes the possibility of any significant quantities of acid or alkali material as the initial one for these clays [34], although about 60% of the Martian surface is occupied by continental elevations formed not by basalt material. This provides the grounds to assume that the composition of continental rocks of Mars hardly differs significantly from the main one.

Another source of data on chemical composition is the results of orbital gamma-spectroscopy. This method for a vast region of Mars (about 1/5 of the planetary surface), where one-third is volcanic, and two-thirds is continental revealed generally low contents of K_2O ($0.5 \pm 0.2\%$), U (0.6 ± 0.3 g/T) and Th (2.1 ± 0.7 g/T), as well as SiO_2 ($36 \pm 9\%$) [35]. Identification of the types of rocks using data on trace elements (U, Th) is based on the correlation of trace elements with main petrogenic elements which is known in the geochemistry of terrestrial and lunar magmatic rocks (which for diagnostic purposes is only used for remote study of the material of other planets). Special analysis of the obtained data (with regard for the possibility of separating U and Th in the surface processes) indicated that in the soil of the volcanic part of the studied region, the contents of U and Th are characteristic for the basalt rocks, and in the soil of the continental part they could be even lower and similar to the content of these elements in the gabbroid continental material of the Moon [36] (table 1).

We would like to use this example to point out the little-studied possibility of taking the correlation in the analyzed material of K, U and Th to distinguish the plutonic rocks from their effusive analogs in those cases where a petrographic study is impossible. The trace elements have high geochemical sensitivity to the type of rock, their content from rock to rock changes severely by orders (for example, from ultrabasic rocks to acid, the SiO_2 content rises a maximum of 2.5-fold, and Th from 10^{-7} to $10^{-3}\%$, i.e., roughly 10,000 times). With the current inevitable high error in analyzing material on other planets, identification of the rock type from

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the measured contents of K, U and Th can often be made more confidently than from the main elements determined with the same relative error. Development of detailed K - U - Th-classification of rocks is now one of the most urgent geochemical tasks of planetology.

Thus, for Mars from the results of independent methods of analyzing the soil, the ancient continental rocks can be described with a definite percentage of probability as the main nonvolcanic material which is a fortiori not highly alkali. On this smallest planet of the terrestrial group, which retains in its mantle a certain quantity of truly volatile components, the continental materials, no matter how meager and approximate the information about them, are generally similar to the lunar, although it is impossible to exclude the somewhat greater content of alkali in them.

Venus. The heterophase mantle of Venus consists of a crust and thick carbon monoxide atmosphere which is only 4-fold less massive than the hydrosphere of the Earth. Because of this atmosphere which encompasses the planet, the surface of Venus has now been studied less than any other planet in the terrestrial group. The first information about the global relief and the irregularity of the surface [37, 38] was received not so long ago, as well as large-scale panorama images of four sections which are approximately a thousand kilometers from each other (at the landing sites of the stations Venera-9, -10, 13 and 14) [39].

Currently three geomorphological provinces have been isolated on the surface of Venus, elevated mountainous localities (often with vast piedmonts), slightly separated hilly plains of medium level and flat level lowlands [37]. The most widespread are the hilly plains, occupying over half of the entire surface of Venus. Many circular structures of obscure genesis are confined to these plains, but roughly 30 of them (on an area photographed with high resolution) can be considered impact craters [40] and the province of hilly plains can be viewed as the hypothetical continental part of Venus [37]. An example of the manifestation of the endogenous volcanism on Venus could be one of the mountainous regions, the Beta area which is interpreted as a possible shield volcano [37].

In the planetary mantle of Venus [1, table 36] among the truly volatile components there is a great dominance of carbon dioxide which is predominantly concentrated in the atmosphere. Water in the atmosphere, on the contrary, is negligible (as, by the way, in the atmospheres of Earth and Mars); most of the water can be found on Venus only in the scattered state in the hydrosilicates of the crust rocks, but judging from the estimates [41], even its maximum possible quantity here is also low and as a result, the hot planetary mantle of the large planet of Venus which is close to the Sun is somewhat poorer in water than the planetary mantle of Mars which is 8 times less massive [1]. For geological processes on the surface of Venus, as on Mars, it is important that the majority of the water can be fixed in the solid phase, and on these planets, in contrast to the Earth, the processes with flowing water are secondary to the aeolian.

As shown by the results of studying panorama images, where the conditions of rock exposure (from under the loose soil) are good (landing site of Venera-14), thin-layered, subhorizontal deposits are visible which are most likely represented by aeolian sediments; the nature of the more poorly exposed rocks is not clear; they could be sedimentation rocks and very weathered lava [39]. In content of K, U and Th [42] (table 3) and chemical composition [43] (table 4), the analyzed formations differ somewhat from each other, but all of them are chemically similar to terrestrial magmatic rocks, which could be an indication of the absence of global mixing of the aeolian material and the low degree of chemical separation of the elements in the surface processes.

TABLE 3
CONTENT OF K, U AND Th IN SURFACE ROCKS OF VENUS [42, 43]

(1) Место посадки	K ₂ O, %	U, g/g (2)	Th, g/g (2)
«Венера-9»	$0,85 \pm 0,14$	$0,60 \pm 0,16$	$3,65 \pm 0,42$
(3) «Венера-10»	$0,36 \pm 0,2$	$0,46 \pm 0,26$	$0,70 \pm 0,34$
«Венера-14»	$0,2 \pm 0,07$	He onp (4)	He onp (4)
«Венера-13»	$4,0 \pm 0,63$	»	»
«Венера-8»	$4,8 \pm 1,4$	$2,2 \pm 0,7$	$6,5 \pm 0,2$

Key:

1. Landing site
2. g/T
3. Venera
4. Not determined

TABLE 4.

CHEMICAL COMPOSITION OF SURFACE ROCKS OF VENUS AT LANDING SITES OF STATIONS VENERA-13 AND VENERA-14 [43], % BY MASS

Компонент (1)	(2) «Венера-13»	(2) «Венера-14»	Компонент (1)	(2) «Венера-13»	(2) «Венера-14»
SiO ₂	45,4±3	48,7±3,6	MgO	11,4±6,2	8,1±3,3
TiO ₂	1,59±0,45	1,25±0,41	MnO	0,2±0,1	0,16±0,08
Al ₂ O ₃ (3)	15,8±3,0	17,9±2,6	CaO	7,1±0,96	10,3±1,2
ΣFe в виде FeO	9,3±2,2	8,8±1,8	K ₂ O	4,0±0,63	0,2±0,07

Key:

1. Component 2. Venera 3. in form of

The age of all the analyzed rocks is unknown; their hypsometric markers correspond to the mountainous region (Venera-9) and the hilly plains (Venera-8, -10, -13, 14). However, in position in the global relief, the rocks of the landing sites of the Venera-9, -10, -13 and -14 stations belong to the outskirts and the zone of the piedmont, large, possibly volcanic region of Beta, while the rocks of the landing site of Venera-8 are distant from the mountainous regions and from the lowlands, but not far from one of the likely impact craters. These two groups of rocks should be discussed separately.

The stratified rocks of the I group are chemically close to the basaltic rocks and in geological position are interpreted as basalt [42-44]. This is undoubtedly likely, but cannot be considered finally established until the question is clarified of the volcanic or plutonic nature of the substance forming it. This study has not yet been made (it rests upon the absence of detailed K - U - Th-classification of the terrestrial rocks). Rocks of this group are chemically nonuniform [43]: the material at the landing sites of Venera-9, -10 and -14 (table 3, 4) is chemically similar to the tholeiite basalts or common gabbro of the normal series, and at the landing site of Venera-13 is close to the subalkali basalt or alkali gabbroids. It should be noted that differentiation of material has an effect in the change not so much in its acidity, as its alkalinity, and according to [28] in the rocks of such

chemical composition as at the landing site of Venera-13, the $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratio could be < 1 or $1 - 4$ (i.e., these high-potassium rocks could belong to the potassium or potassium - sodium series), and at the landing site of Venera - 14, $1-4$ or even > 4 (i.e., the low-potassium rocks could be of the potassium-sodium and sodium series). Do these chemical differences reflect the evolution of the crust material of basalt type or diversity of rocks of the continental substance, or finally, are they related to both, this is still an unanswered question and its solution needs a much more serious understanding of the geological structure of the Venutian surface.

The appearance of rocks on the hilly plains at the landing site of Venera-8 is unknown. Considering the proximity of the likely impact crater with diameter 140 km surrounded by a 100-kilometer radar-bright zone [40, table 2], they could be represented by material of crater discharges, but judging from the low radar irregularity of the landing site region [38], they could be some aeolian or metamorphic formations. After the appearance of the first map of the Venutian relief, a distinct confinement of the landing site of Venera-8 to the province of hilly plains was found [37]. Consequently, a special study was undertaken to identify the type of rock tested here [44]. For this a search was made among the terrestrial volcanic and plutonic rocks for those in which the correlation of K_2O , U and Th (mainly from the data of publications [45 - 48] would be the closest to that measured in this landing site (with regard for the measurement error, table 3). It was found that it is possible to use a pair of any of these elements to select a fairly broad spectrum of rocks (including some feldspar highly alkaline basalts), but for all three elements (for the contour on the $\text{K} - \text{U} - \text{Th}$ -diagram [44]) the analyzed rock was close to the plutonic rocks of the syenite type which are mean in composition. Generalization of the primary geochemical materials from the latter (data of publications [49- 55] and many others) indicated that the closest coincidence for K_2O , U and Th is provided by one type of rock, alkali (felspathoid-free) syenites. These are feldspar rocks with sum of alkalis about 12% (almost without plagioclase, but with 60 - 70% microcline - perthite) and with

stable dominance of sodium over potassium (table 1).

The landing site of Venera-8 is within the hypothetical continental region of Venus near the likely impact crater; considering the evaluated nonbasalt nature of the analyzed material as well, it is possible to view the composition of this rock as reflecting to a certain measure the chemical composition of the continental material of Venus (perhaps, because of its significant differentiation to the same measure as the granite substance of Earth is characterized by its continental rocks, although it does not reflect their mean composition). We note that the rocks at the landing site of Venera-8 were the first rocks that were analyzed on the Venutian surface and precisely this one analysis of the K, U and Th contents made it possible to state that Venus, like Earth, is differentiated into shells [56].

It seems to us that it would be sufficiently cautious to say that in the continental substance of Venus there is at least highly alkaline plutonic feldspar material. The evaluated nonvolcanic nature and significantly feldspar composition bring it close to the continental material of the Moon. However, it differs severely from the continental material of the Moon and Mars because of its significantly greater contents of easily volatile alkalis, and possibly, silicon because of the reduced contents of Ca and Mg in the same way as small reserves of truly volatile components in the planetary mantles of these small bodies are very dissimilar to the massive reservoir of CO_2 on Venus, a large planet which is roughly the size of the Earth.

Earth. The main peculiarity of the heterophase mantle of the Earth which isolates it among other planets and determines the specific nature of the geological processes occurring on Earth is the presence of water in the liquid state, the hydrosphere. The main mass of water on Earth is concentrated in this mobile shell of the mantle, while the carbon is scattered in different solid phases of the crust rocks, while the mass of the nitrogen atmosphere is only about 1/400 of the mass of the hydrosphere [1, table 28]. The importance of considering the volatile components in the entire

heterophase mantle is especially noticeable for Earth.

Earth is sharply isolated from among the other planets by the very high intensity of geological processes and their cyclic nature in the majority of manifestations. Whereas the severely slowed down processes of surface change on the Moon, Mercury and Mars permit the earliest stage of their existence to be observed, on Earth, the rocks more ancient than 1.5 - 2 billion years provide us with an appearance that is already so changed in the metamorphic processes that clarification of their initial nature requires special reconstructions.

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Among these deeply metamorphized formations, the most ancient of the rocks ever observed on Earth are about 3.75 - 3.85 billion years old. It is approximately to this time border on other planets that such events are confined as severe drop in intensive meteorite bombardment of the surface, and everywhere where this is accessible to geological observation, the penetration through the already formed continental crust of area basalt discharges. Thus, the age of the most ancient rocks for Earth is not random, it records the most important planetological boundary, the time for actual stopping of planetary growth because of a severe drop in the impact bombardment, completion of formation of the continental material and activation of mass endogenous volcanism.

In the terrestrial rocks which metamorphized about 3.8 billion years ago, "granitoid" substance and volcanic substance of the basalt type which is characteristic for continents is fixed. However, in addition among them are pararocks (quartzites, shales, marbles), i.e., by this time the most ordinary sedimentary rocks had already accumulated (sandstones, clays, carbonates); in rocks of age 3.5 - 3.8 billion years there are essentially all types of sedimentary rocks known to modern geology [57 - 59]. Moreover, the most ancient sediments have already traces of the existence of living systems [57] and difference in the isotope composition of organic and carbonate carbon here is the same as in the modern sedimentary rocks [60, 61]. Thus, both the hydrosphere and atmosphere, and even the biosphere of Earth functioned as formed

geochemical shells already by 3.8 billion years ago, i.e., by the end of the period of intensive meteorite bombardment of the surface. However, it is apparent from the lithology of the ancient terrestrial rocks that the situation in the period of intensive bombardment on Earth differed strongly from the lunar because of the development in that period of processes of weathering, sedimentation and metamorphism that are normal for the Earth, processes with the active participation of truly volatile components. With the completion of this period, the "granitoid" material of Earth already existed in its crust formations in precisely the same way as rocks of the same age on the Moon already had the continental material.

Rocks of the "granite" layer of continents are still the only bedrock of the Earth accessible to direct geochemical testing. Interpretation of the geophysical data for the deeper, so-called basalt layer is unequivocal, since the physical characteristics measured here can correspond to rocks of the base, and more acid composition (metamorphic, for example) [1]; during drilling of the Kola superdeep well, the geophysically-fixed transition to "basalt" layer, judging from the first reports [62], was not at all reflected in the composition and nature of the metamorphic rocks of the shield. In order to describe the chemical features of the Earth's continental material, without using hypothesis, we will employ only data on the "granite" layer [21]. The majority of the basalt material on the Earth (88%) is linked to young discharges on the bottom of the ocean; the mass of products of basalt volcanism on the continents is no more than 9% of their total material, and therefore subtracting them from the mean composition of the "granite" layer (table 1) naturally changes it little.

The continental material of the Earth which is predominantly represented by metamorphic rocks of the shields and is repeatedly reprocessed with the participation of liquid water and the biosphere during all of Earth's history, can be described chemically as feldspar plutonic rock mean in composition and of the subalkaline series

(of the subalkaline quartz diorite - quartz monzonite type) (from [28]). One can customarily speak of the "granitoid" nature of this substance only because its most significant feature is the presence of gneisses and granite - gneisses. The continental material of the Earth has a striking chemical difference from the continental material of the small planetary bodies (Moon, and probably Mars) in its severely greater content of alkalis and silicon on the background of a severely lower content of Ca and Mg. But the continental material of Earth neither in its average composition, nor in the composition of the characteristic "granite" rocks is similar either to the rock at the landing site of Venera-8 as it is from the results of the conducted analysis. On Earth it not only is more acid, but, mainly, is significantly less alkaline.

There is still no clarity in the origin of continental material on Earth [1]. The hypothesis of the formation of "granitoid" material because of magmatic differentiation of the depths is based on the good physical and chemical study of the laws governing melting - crystallization of the material and on the chemical parameters of the "granitoids" which permit completion by them of the basically sequential series of magmatic differentiation: ultrabase rocks (meteorites) → basalt → granite. Individual small massifs of acid differentiates of basalt magma are really known on Earth, however, 92% of the mass of the total basalt material on Earth (basalts of the oceans, traps) are young formations which are superposed on the already formed "granitoid" substance; the basalt volcanism develops independently of the geological history of the continental material [1]. The overwhelming mass of intrusive (plutonic) material on Earth comprises deeply metamorphized "granitoid" rocks of shields. The classification of these rocks as magmatic is fairly conditional since palingenic - anatectic rocks are also included here; it merely means the possibility of remelting and does not affect the question of the source of the remelted substance.

The problem of the original material is usually solved using the results of isotope analysis (Rb - Sr, Sm - Nd) whose interpretation requires the adoption of a whole series of assumptions [63].

In particular, one of them requires that from the moment of the last melting the studied sample should remain an open system, i.e., would be completely isolated from the effect of metamorphism and metasomatism, the effect of hot fluids and chemical weathering. On Earth, under conditions of universal penetration of liquid water and living systems, this condition is difficult to fulfill, and whereas quite recently the low initial ratios $(^{87}\text{Sr}/^{86}\text{Sr})_0$ in the apparently weakly changed granitoids were interpreted exclusively as a sign of their melting directly from the mantle, in recent years this has raised serious doubts [64 - 66]. It was found, for example, that the same "mantle" values characterize many sedimentary rocks and paragneisses [65], and in a number of cases, the age of the rocks that is obtained when the secondary processes are ignored is geologically senseless [64]. The initial material of the granitoids with high quantities $(^{87}\text{Sr}/^{86}\text{Sr})_0$ of course belonged to the crust, but the question of the source of the material with low values of this parameter has not found an unequivocal solution in the isotope data [65]. There has not yet been an evaluation of the balance of the mass of granitoids with certain isotope characteristics and it is not clear which of the isotope parameters are representative for the main mass of the "granitoid" substance of the Earth's crust, the deeply metamorphosed rocks of the shields.

One should focus attention on the fact that for the most ancient granitoids of the Earth, the low quantities of $(^{87}\text{Sr}/^{86}\text{Sr})_0$ could indicate not only the mantle source of material, but also directly the actual original meteorite material which arrived at the Earth in the earliest period of its life. Publications [1, 32] have discussed the possibility of the formation of the "granitoid" substance of the Earth in impact processes of evaporation and condensation. However, the majority of researchers somehow or other link the solution to the problem of the genesis of the Earth's acid material with the transformation of ancient sediment during metamorphism, granitization and palingenesis, which requires vertical redistribution of material, with introduction of "granite" components (silicon, alkalis), but neither the source, nor the forms of their influx, nor the global balance of this process are completely clear [1].

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The genesis of the "granitoid" continental crust of the Earth remains among the most complicated and controversial basic problems of geochemistry.

Discussion

We will base the discussion on the fact of the extremely ancient formation of the continental material which was proven for the first time for the Moon, confirmed geologically for Mercury and Mars and did not contradict the data on Earth, and relate it to the fact of the equally early isolation of the main mass of the truly volatile components (their accumulation on the planet or loss from it). It seems important to us to focus attention on the fact that the formation of all shells of the heterophase planetary mantle occurred in the very first half billion years of life of the planet.

The general property of the continental material of the planetary bodies of the terrestrial group as it is pictured today is its nonvolcanic nature. Although the chemical features of this material can be conveniently described in terms of the nomenclature of magmatic rocks, on the Moon in the absence of truly volatile components, this material is predominantly formed of impact breccias, and on the planets with developed heterophase mantle it is presented by material of exogenous and metamorphic processes. These normal geological processes, judging from the lithology of the most ancient rocks of Earth, begin very early and merge in time with the impact-explosive transformations. Because of the local (spot) nature of the impact events with random distribution of impacts on the surface [1], the material in one place could be transformed in the impact processes, and in another, in the sedimentary (aeolian or aqueous) or metamorphic and hydrothermal (initiated in this case by the thermal impact field), but the products of these processes again and a fortiori in a different manner [13] could be involved in the impact melting and evaporation, but one can only guess as to the nature of the products of these interactions. It is likely that precisely in such a complicated and little-studied turnover of processes there are* geochemical cycles of elements on the planets which retain truly volatile components, where the continental material

* Should one not search here for the initial reasons for the shortage of Si and Ca surplus [21] and normal volatiles [67] in modern sedimentary

could be an initially polygenous formation which is specific for this planet.

It is difficult and ambiguous to interpret the chemical features of the continental material (table 1). Its feldspar composition, i.e., high alumina content, indicates universal accumulation in it of Al, an element which is included in the "low-melting" phases (reducing the melting temperature of the silicate systems) and one of the most difficult-volatile elements. The continental material of the planets has natural differences in Si content, and they correlate clearly with the varying content and composition of the truly volatile components: on the small planetary bodies with low or completely negligible reserves of these volatile components, the continental material is the primary in composition (Moon, Mars), while on the large planets which have retained a large quantity of these volatile components, this material is mean in composition (Earth, and perhaps Venus). There is an even stronger difference in the content of alkali metals, whose sum in the continental material of large planets is apparently an order higher than on the small, as the sum of the truly volatile components is an order greater on them. These laws are completely empirical. They can be interpreted as severely greater enrichment of the continental material of the large planets "low-melting" components and at the same time, as severely greater accumulation in it (and in the entire planetary mantle) of volatile components, their lower loss by major planets.

We recall that under conditions of the initial period of life of the planet, the deep material of the mantle may not yet have been involved in active radiogenic melting [1], the system of the planetary mantle was predominantly open in relation to space, and in numerous impact events, the material was undoubtedly exposed to both melting and evaporation. Both of these processes could have resulted in fractionation of the material and it is still unclear which of them could have been decisive, although according to the descriptive remark of Bart [68], a melting pot is more capable of homogenizing material than separating it, while the increased migratory capability of the material in the gas phase rocks (stratisphere) of Earth as compared to its igneous rocks?

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sharply intensifies the possibility of differentiating it. In addition, the nature of dissipation of gases from the planet (and from its atmosphere) under conditions of intensive meteorite bombardment differs inevitably sharply from the modern. As it seems to us, for this period it would be important to evaluate, for example, the possibility of direct dynamic loss of gases by the planets.³ Unfortunately, the mechanism for geochemical differentiation of the material for volatility, in contrast to the well-studied mechanism for crystallization differentiation of melts has not yet been quite studied; the search for traces of this method of fractionation, primarily the effects of kinetic separation of isotopes, seems very promising to us.

The difference in the chemical composition of the continental substance of the major planets, if our estimates of the rock composition at the landing site of Venera-8 are correct, can be manifest in the varying correlation of potassium and sodium (table 1). With different correlations on these planets of water and carbon dioxide (H/C for Earth is about 2, and for Venus ≈ 0.1 [1]), this could be related to the separation of K and Na on Earth in aqueous solutions because of the predominant sorption of K on solid phases, which could potentially result in its relatively lower involvement in the repeated processes of impact evaporation. This consideration is not an explanation of the fact which itself needs confirmation, but only an argument to illustrate the fact that the impact vapor on the planet is a complex function of many variables and that the fate of individual gas components diverges sharply. Some gases can in some way or other lose their migratory capability (be condensed into a solid or liquid phase, be dissolved in solution or impact melt, interact with the condensed material), others could leave the planet, and only those gases which succeed in avoiding both competing processes, losses from the planet and capture in the condensed phases, are now seen in the gas shell proper of the planet, the atmosphere.

³ Some indications of this are given by data on the Moon which loses Rb with atomic mass 86, although because of its dissipation only gases with molecular mass approximately to 43 could leave [29].

We also note that, as follows from table 1, the continental material of the terrestrial planets could be characterized by a fairly uniform content of iron which depends neither on the size of the planetary body, nor on the dimension of its nucleus, however, this observation requires verification.

Concluding Remarks

We still know little about the continental material of the planets in the terrestrial group, and any final conclusions seem premature now. We would like to once again briefly summarize the new and still little known facts in classic geochemistry which have been obtained by comparative planetology in order to stress the new questions raised by them.

The growth of solid cosmic bodies through collisions and the resulting inevitability of chemical transformations of material have been empirically established. The original material from which the planetary mantle grew was not simply accumulated, but mandatorily underwent certain chemical transformations during growth. Is this not why the rocks in the upper mantle of the Earth, as they are from actually studied samples of peridotites [69 - 71], are significantly different from the chondrite material?

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Formation of the system of external planetary shells, their heterophase planetary mantle, occurs in the first, approximately half billion years of life of the planets, in the transitional period of completion of their growth and the beginning of geological history, when the material on all the planets, locally, but repeatedly was transformed during the impact events. The role of endogenous processes in this period is problematic, and during the impact transformations, the silicate material not only melted, but also partially or completely evaporated. In this period of time, any rock component could be potentially viewed as a volatile component and the chemical fractionation of the material could take place both because of the normal crystallization differentiation of the melt, and by unusual method, by separation of the material by volatility under conditions of a system open for space. We would

like to draw particular attention to this almost unknown mechanism for geochemical differentiation of material at the early stage of life of the planets because of the detected, distinct correlation between the components of varying volatility in all the material of the heterophase mantles of the planets, including their solid-phase component, the continental material.

Whereas on the Moon which lost the truly volatile components (H_2O , CO_2 , ...), impact reprocessing was and remains the leading method for transformation of the surface material, on the planets which are capable of retaining these volatile elements and forming a developed heterophase mantle, the surface material in the very early period of life, parallel to the impact processes of melting and evaporation are involved in normal exogenous (sedimentary, for example), metamorphic and hydrothermal processes. Thus, there is a complete likelihood that in the formed geochemical cycles of elements, the sedimentation process is historically just as primary as the process of melting. In the set of impact and normal geological processes, chemical features are established for the continental material of the crust on planets which have retained truly volatile components. It is known that the quantity and composition of these volatile components in the material that was exposed to impact transformations has a strong influence on the composition of the final products. It is therefore necessary to discuss the possible genetic link between the detected chemical individuality of the continental material of each planet and the uniqueness of the set of truly volatile components on them.

In the subsequent, approximately 90% of the lifetime of the planets, the increase (or reduction?) of the crust occurs because of endogenous processes. There is no doubt that material of the basalt type, the product of crystallization differentiation of the deep material of the depths is added to the crust, however, the scales of this phenomenon, the time of maximum development, the nature of manifestation of basalt volcanism and some details of the chemical composition of its products are evidently different for various planets, and it would be interesting to verify empirically whether they are related to the features formed during the period of planetary growth.

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